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ANALYSIS OF I MARINE EXPEDITIONARY FORCE SUPPORT TEAM RESET OPERATIONS

by

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Non-deployed United States Marine Corps (USMC) ground units are in a degraded state of supply readiness as a result of over a decade of war. Due to current fiscal constraints and budget pressures the USMC cannot purchase new ground equipment to replenish its units. The USMC must repair current ground equipment used in Operation Enduring Freedom, much of which has greatly exceeded its normal peacetime usage. In order for the USMC to remain a "force in readiness" equipment must replenish the non-deployed unit home station quickly. This research analyzes the time it takes to repair an equipment item received from Afghanistan and be sent to a non-deployed unit. We do this by analyzing the Retrograde and Redeployment in Support of Reset and Reconstitution (R4) efforts performed at the Marine Expeditionary Force (MEF) level, specifically I MEF Support Team (1st MST). We use queueing theory and simulation methods to develop an analytical model in which we draw conclusions from. Using 1st MST R4 data, we capture the amount of time required to repair ground equipment and identify the driving factors most affecting this time.

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ANALYSIS OF I MARINE EXPEDITIONARY FORCE SUPPORT TEAM RESET OPERATIONS

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ABSTRACT

Non-deployed United States Marine Corps (USMC) ground units are in a degraded state of supply readiness as a result of over a decade of war. Due to current fiscal constraints and budget pressures the USMC cannot purchase new ground equipment to replenish its units. The USMC must repair current ground equipment used in Operation Enduring Freedom, much of which has greatly exceeded its normal peacetime usage. In order for the USMC to remain a "force in readiness" equipment must replenish the non-deployed unit home station quickly. This research analyzes the time it takes to repair an equipment item received from Afghanistan and be sent to a non-deployed unit. We do this by analyzing the Retrograde and Redeployment in Support of Reset and Reconstitution (R4) efforts performed at the Marine Expeditionary Force (MEF) level, specifically I MEF Support Team (1st MST). We use queueing theory and simulation methods to develop an analytical model in which we draw conclusions from. Using 1st MST R4 data, we capture the amount of time required to repair ground equipment and identify the driving factors most affecting this time.

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LIST OF ACRONYMS AND ABBREVIATIONS

1st MST	I Marine Expeditionary Force Support Team
CDF	Cumulative Distribution Function
CONUS	Continental United States
DLA	Defense Logistics Agency
DoD	Department of Defense
ECDF	Empirical Cumulative Distribution Function
EVT	Extreme Value Theory
FBCR4 & AoA	Fully Burdened Cost of Retrograde, Redeployment, Reset, and Reconstitution and Analysis of Alternatives
GEMS-MC	Ground Equipment Management Simulation-Marine Corps
GSA	U.S. General Services Administration
I MEF	I Marine Expeditionary Force
I&L	Installations and Logistics Command
IID	Independent and Identically Distributed
IMA	Intermediate Maintenance Activity
LNK	Camp Leatherneck
LX	Logistics Operations Analysis Division
MCLC	Marine Corps Logistics Command
MCLC FWD	Marine Corps Logistics Command Forward
MEF	Marine Expeditionary Force
MLE	Maximum Likelihood Estimate
MST	MEF Support Team
OEF	Operation Enduring Freedom
OIF	Operation Iraqi Freedom
PEB	Preexpended Bin
PEI	Principle End Item
QQ	Quantile-Quantile
R4	Retrograde and Redeployment in Support of Reset and Reconstitution

R4OG	R4 Operating Group
RDD	Required Delivery Date
RFI	Ready For Issue
SL-3	Stock List-Level 3
SMU	Sassy Management Unit
TAMCN	Table of Authorized Materiel Control Number
USMC	United States Marine Corps

EXECUTIVE SUMMARY

The United States Marine Corps (USMC) has been at war for over a decade. This has caused a significant strain on the ground equipment used during the conflict, as wartime equipment usage greatly exceeds peacetime usage. This strain has also significantly degraded the supply readiness of non-deployed units. The USMC implements a policy that ensures deployed units maintain the highest priority when sourcing ground equipment. This means if a deployed unit and a non-deployed unit both need a certain equipment item, the deployed unit will be sourced the equipment item first.

The policy the USMC implements creates a burden on the non-deployed unit, and over time can lead to major shortfalls in the non-deployed supply inventory. In fact, in a 2012 report to the House Armed Services Committee the current USMC commandant General James F. Amos reports that only 33 percent of non-deployed units report the highest levels of readiness, indicating that 67 percent of non-deployed units are in a degraded state of readiness.

Given the current Department of Defense fiscal pressures and budget constraints, the USMC cannot purchase all new equipment to improve the supply readiness levels of all non-deployed units. Equipment will have to travel from Afghanistan, a landlocked country, and be repaired to an appropriate operational level in order to replenish these units. Replenishment must occur quickly if the USMC is to remain ready for the next Nation’s crisis. This is the focus of our thesis.

This thesis analyzes the time it takes to repair an equipment item received from Afghanistan and be sent to a non-deployed unit. The focus of this thesis is on one of three Marine Expeditionary Force Support Teams (MST). The study of repair time is done by analyzing actual data collected and using it to populate and run a queueing and simulation model. The average time it takes to repair and prepare an item to be sent to a non-deployed unit is shown to be 140 days (approximately five months).

The largest component of the total average time to repair and prepare a piece of equipment is shown to be the time spent waiting to receive orders of missing items associated with an equipment piece, making up approximately 75 percent of this time. The long wait time for these items is primarily due to the wait for items sourced by the Defense Logistics Agency (DLA) and the U.S. General Service Administration (GSA). We show that the expected processing time can drop from approximately five months to less than four months if a smaller fraction of items are missing or those sourced from DLA or GSA arrive to the MST more quickly. We conclude with recommendations for the need to find ways that will reduce the number of items sourced by DLA and GSA as well as decrease the overall missing items.

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Abba my Rock.

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I. INTRODUCTION

A. BACKGROUND

The United States Marine Corps (USMC) has been at war for over a decade. This has caused a significant strain on the ground equipment used during the conflict, as wartime equipment usage greatly exceeds peacetime usage. This strain has also significantly degraded the supply readiness of non-deployed units. The USMC implements a policy that ensures deployed units maintain the highest priority when sourcing ground equipment. This means if a deployed unit and a non-deployed unit both need a certain equipment item, the deployed unit will be sourced the equipment item first. This creates a burden on the non-deployed unit, especially in the case for high demand-low density items in the USMC ground equipment inventory.

The burden on the non-deployed unit intensifies when non-deployed units also transfer ground equipment items it has in its possession to support deployed forces. As a result, only 33 percent of non-deployed units report the highest levels of readiness, indicating that 67 percent of non-deployed units are in a degraded state of readiness (Amos, 2012, p. 13). This decrease in readiness is mainly attributed to insufficient equipment supply (Amos, 2012, p. 13). A unit reports the highest state of supply readiness if it has in its possession all ground equipment items necessary to perform its assigned mission. Given the current Department of Defense (DoD) fiscal pressures and budget constraints, the USMC cannot simply purchase all new equipment to improve the supply readiness levels of all

units. This raises concerns about the USMC's ability to effectively posture for the Nation's next crisis. Equipment will have to travel from Afghanistan, a landlocked country, and be repaired to an appropriate operational level in order to replenish home station units.

As Operation Enduring Freedom (OEF) draws to a close, the USMC must effectively manage the process of returning ground equipment to units. This must occur in order to ensure the USMC remains mission capable for the next conflict. The USMC Commandant, General James F. Amos captures the importance of handling returning OEF ground equipment when he states in a message to the Marine Corps that he "require[s] the personal commitment of every Marine to ensure our equipment is repaired and returned quickly [from Afghanistan] to the war fighter [at the home station]" (USMC, 2012a, p. i).

In this thesis, we focus on the "quickly" component of General Amos' quote. We analyze how long it takes equipment to return to the warfighter and suggest possible avenues to reduce this time. The analysis focuses on one of three operating force commands within the Marine Corps: I Marine Expeditionary Force (MEF) headquartered out of Camp Pendleton, California.

B. OEF GROUND EQUIPMENT, ORGANIZATIONS AND TERMS

USMC ground equipment in Afghanistan has a variety of end states. The USMC could dispose of the equipment, sell it through foreign military sales, fill deficiencies in various USMC supporting establishments or eventually supply one of three MEFs (USMC, 2012a, p. 12). We focus on the equipment sent to I MEF. Figure 1 depicts how USMC ground

equipment travels from Afghanistan to replenish I MEF. Marine Corps units in Afghanistan first send all ground equipment to Camp Leatherneck (LNK) for processing and inspection. Upon arrival to LNK, the Retrograde and Redeployment in Support of Reset and Reconstitution (R4) Operations Group (R4OG) perform basic maintenance repairs and consult with Marine Corps Logistics Command (MCLC) about where the item should be sent. MCLC FWD is the forward deployed contingency of MCLC and is located on LNK (MCLC, 2013). The map shown in Figure 1 is not drawn to scale; LNK and R4OG are actually located in the vicinity of the MCLC FWD symbol shown in the Figure.

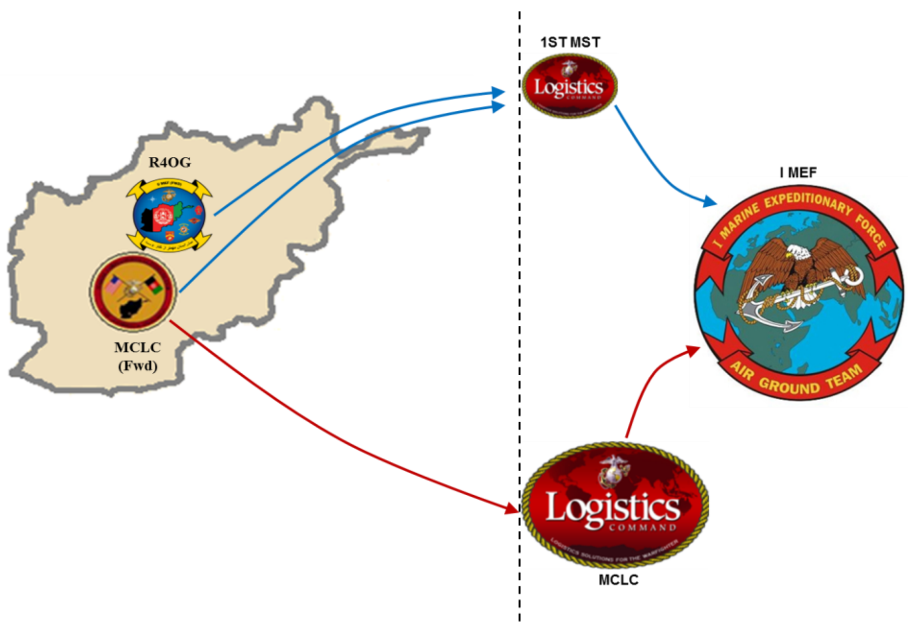

Figure 1. Graphic depiction of how equipment returns from Afghanistan and replenishes I MEF home station units. Afghanistan is not drawn to scale, and both units depicted in Afghanistan are actually located at LNK in the Helmand Province. (After MCLC, 2011, p. 10)

MCLC is a USMC command that is responsible for supporting the warfighter with integrated logistics, supply chain, maintenance and distribution management (MCLC, 2013). MCLC is also the executive agent for handling ground equipment returning from Afghanistan (USMC, 2012a, p. 10). The Headquarters of MCLC is located on Marine Corps Logistics Base Albany, Georgia which is also the location of one of the main Depot Maintenance Commands (MCLC, 2013).

As shown in Figure 1, MCLC FWD and R4OG send ground equipment to two locations. They send some equipment to MCLC in the Continental United States (CONUS) and send other equipment to I MEF Support Team (1st MST). 1st MST is a conglomerate of civilian/government employees and hired contractors that receive and repair equipment arriving from Afghanistan destined for I MEF units. This organization resides on the same military installation as the I MEF Headquarters at Camp Pendleton and MCLC operationally controls it.

After 1st MST completes the required servicing of ground equipment, they issue the item to I MEF. I MEF is a USMC Marine Air-Ground Task Force, which is the central organization for performing all missions across the range of military operations (USMC, 2013). I MEF is one of three operating force MEFs within the USMC comprising of over 50,000 personnel and six Major Subordinate Commands made up of various units (I MEF, 2013).

In this thesis, we focus solely on the actions taken on the right side of the dotted line in Figure 1 and primarily focus on 1st MST's efforts. We refer to this as the 1st MST R4 Process, where R4 is a term used to describe

the entire process of drawing down from Afghanistan, returning ground equipment, and replenishing home units. R4 stands for retrograde, redeployment, reset and reconstitution. The terms retrograde and redeployment describe how equipment from Afghanistan is delivered to home units. Reset relates to the repair actions performed on ground equipment while reconstitution relates to the larger picture of the USMC after all OEF R4 actions have been completed. These terms are officially defined in (CJCS, 2013a). We summarize these definitions below:

- Retrograde: return of equipment from a forward location to a directed location in CONUS.
- Redeployment: return of equipment to the home station.
- Reset: the use of any combination of replacement, recapitalization, or repairs that brings an item to some level of capability. Replacement is essentially buying new equipment. Recapitalization is essentially rebuilding a piece of equipment to put it in "as-good-as-new" condition. Repairs restore a piece of equipment to a serviceable condition.
- Reconstitution: actions taken to restore combat capability to full operational readiness. To be fully reconstituted means that the equipment and personnel are at the highest levels of readiness and ready for the Nation's next crisis.

As we focus primarily on the 1st MST portion of the R4 process, we now describe that in more detail.

C. 1ST MST R4 PROCESS

There are two main sources of R4 equipment flow to I MEF (see Figure 1). I MEF units receive ground equipment from 1st MST and MCLC. MCLC sends items directly to I MEF units; we do not analyze this component in this thesis. We

focus on the equipment that flows through 1st MST to replenish I MEF units and now describe 1st MST operations in more detail.

1. Arrival, Initial Inspection, Repairs and Maintenance

When 1st MST first receives an equipment delivery it performs an inventory of all items delivered. Often equipment is packed in containers or pallets, which means that ground equipment varies in the amount received. Most items received by 1st MST require auxiliary items called Stock List-level 3 (SL-3). These items generally do not completely arrive with the equipment. For instance, if a radio has SL-3 associated items such as radio attachments, batteries, antennas etc., it may arrive missing its batteries. The number of auxiliary SL-3 items a piece of equipment has can range from just a few to upwards of 100. An equipment piece that contains all of its associated SL-3 items is coined *SL-3 complete*. This is an important term because items cannot be issued to a unit until they are SL-3 complete.

After the inventory is complete an item undergoes a detailed inspection. During the detailed inspection one of three actions may occur: the item can be in such bad condition that it is instantly deemed beyond economical repair and MCLC must dispose of the item, reset may occur, or no reset actions are required and the ground equipment can be immediately issued to a unit. The first and last actions rarely occur, and in most cases items require reset actions. 1st MST performs the great majority of reset actions. There are some occasions in which a piece of

equipment requires reset actions beyond 1st MST's capabilities. In these situations, 1st MST sends the equipment to the Intermediate Maintenance Activity (IMA) of I MEF. We will not examine the IMA component in this thesis. Once 1st MST completes repairs, 1st MST must often obtain missing SL-3 items to make the equipment SL-3 complete. We now discuss how 1st MST obtains the missing SL-3 items.

2. Obtaining Missing SL-3 Items

The initial assessment determines what maintenance and supply ordering actions 1st MST must perform. If SL-3 items are missing, they are obtained through one of several possible sources of supply that include: 1st MST's Preexpended Bin (PEB), the Sassy Management Unit (SMU), MCLC, Defense Logistics Agency (DLA) and the U.S. General Service Administration (GSA). These sources are described as follows:

- 1st MST's PEB is a parts storage bin that can be accessed immediately, meaning there is no wait time to obtain parts associated with this source.
- The SMU is utilized if the required items are not located in the PEB, and is the I MEF major supply warehouse. Orders filled by this source take one to two days to fill.
- MCLC also supplies items through a consolidation of already purchased parts that are available for use. Orders filled by this source can take seven to 10 days to fill.
- DLA and GSA sources are used to fill orders for items that are not found in the PEB, SMU or MCLC. They are agencies that supply and support the DoD. Orders from these sources can take anywhere from seven to more than 30 days to fill.

3. Issuing Equipment

Once the ground equipment items are reset and are SL-3 complete, they are considered ready-for-issue (RFI) indicating that they can be issued to I MEF units. The I MEF G-4 performs the logistical functions of I MEF. This includes issuing equipment to units (G-4, 2013). Periodically 1st MST provides a list of RFI equipment to I MEF G-4. I MEF G-4 then identifies the I MEF unit that will receive the ground equipment item based on unit deficiencies and I MEF priorities. We label the process of assigning equipment to units as *issuing distribution instructions*. After I MEF G-4 provides final distribution instructions the subordinate unit must go to the 1st MST equipment lot to take possession of the equipment. As the I MEF unit receives equipment, the unit's supply readiness is then improved if the equipment is identified as a *Principle End Item* (PEI).

PEIs are items that have been nominated by several entities within the USMC to be of "sufficient range to provide an adequate measure of overall equipment status and/or capability for the Marine Forces" (USMC, 2012b, p. 2). These items are listed in the Marine Corps Bulletin 3000 and its contents updated annually. Data from November 2011 estimates that approximately 50,000 PEIs from OEF are anticipated to replenish the MEFs (USMC, 2012a, p. 12).

D. OBJECTIVE

The USMC Commandant issued an OEF Ground Equipment Reset Strategy that outlines several ground equipment progress measurements (USMC, 2012a). We address two of the seven measurements presented in the strategy that relate to

home station actions, as pertaining to I MEF. These measurements are (1) capturing the impact of reset actions on MEF readiness at home station and (2) addressing average time to induct equipment into maintenance and time to reset the equipment (USMC, 2012a, pp. 16–17). To address these measurements this thesis utilizes relevant operations research techniques to study the 1st MST R4 Process.

In our thesis, we analyze 1st MST's progress measurements by first performing a thorough review of other R4 analyses and analyses of repair and maintenance of systems in Chapter II. In Chapter III, we proceed with exploratory data analysis on 1st MST data. In Chapter IV, we describe the model and results for the 1st MST R4 Process and perform sensitivity analysis. We conclude with Chapter V, wherein we present our findings and recommendations.

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II. LITERATURE REVIEW

In this chapter, we discuss recent research initiatives capturing the larger overall R4 Process. We also present previous studies that utilize quantitative techniques and models to examine maintenance and repair processes.

A. R4 MODELS

A recent R4 modeling initiative is the Ground Equipment Management Simulation-Marine Corps (GEMS-MC). GEMS-MC is a discrete event simulation modeling initiative spearheaded by the USMC's Installations and Logistics (I&L) Logistics Operations Analysis (LX) division. I&L's LX is currently developing a large simulation model to capture time and costs for ground equipment items in the R4 Process, traveling from Afghanistan to destinations such as MCLC and USMC unit home stations (Burciaga, Enoka, & Solano, 2013). GEMS-MC is of larger scope than what we tackle in this thesis, and does not explicitly model the MST R4 actions taken. Our analysis could potentially be used to incorporate the MST into the larger GEMS-MC simulation. Similar to our work, GEMS-MC uses time required in the R4 of USMC ground equipment as its primary measure of effectiveness.

Farrar and Lloyd (2012) create a cost model to capture the full costs of R4 including manpower expenses known as the Fully Burdened Cost of Retrograde, Redeployment, Reset, and Reconstitution and Analysis of Alternatives (FBCR4 & AoA) Model. The aim of the FBCR4 & AoA model is to provide the decision maker with alternatives regarding the

retrograde of items, specifically vehicles (Farrar & Lloyd, 2012). This research uses a collection of equipment and cost data received from seven different sources and generates an aggregated cost value for several alternatives such as: shipping directly to CONUS, using foreign military sales, or disposing of (scrapping) equipment in Afghanistan (Farrar & Lloyd, 2012).

The FBCR4 & AoA model differs from GEMS-MC in that time is not a factor under consideration. The FBCR4 & AoA is more of a prescriptive model for the decision maker as opposed to a descriptive model as is GEMS-MC. As with GEMS-MC this is a large scope model of the R4 process but does not explicitly capture the MST actions.

Another study that relates to R4 is a report initiated by the U.S. Government Accountability Office regarding the retrograde from Operation Iraqi Freedom (OIF). The study was performed in response to the retrograde efforts of Operation Desert Storm, a war of less duration than OIF, but whose retrograde took approximately 14 months to complete (GAO, 2008, p. 2). The study presents a model used to assist decision makers in identifying the monthly total throughput of equipment in the OIF theatre of operations. The model can also be used to show the rate of equipment flow that can be sustained (GAO, 2008, p. 73). This model differs from GEMS-MC in that it also factors throughput capacity for inbound personnel and equipment. The model assumes that though equipment departs Iraq, there is still some equipment inflow because units are still in the deployment cycle executing combat missions.

Jackson (2007) wrote a report related to R4, which provides a large scope study that concerns the effect of utilizing a mixed method data analysis approach to measure the performance of the pure pallet program for retrograde of equipment purposes. This work differs significantly from the previous works mentioned, as it focuses more on measuring satisfaction of the intended recipient of the equipment being retrograded (Jackson, 2007, p. 127). This study finds that a major measure of satisfaction for the customer is the ability to predict incoming arrival of equipment so that appropriate actions can be taken to effectively respond to the flow of equipment (Jackson, 2007, p. 125). Though our work does not aim to predict the inflow of equipment or measure satisfaction, we do perform exploratory data analysis on 1st MST equipment arrivals and gain valuable insight into the process and the time involved. In our case the lower the time it takes to process items, the more satisfied the USMC will be.

B. MAINTENANCE AND REPAIR MODELS

In addition to R4 related literature there are also initiatives to model maintenance and repair processes. In particular, a model presented by Burton (2005) aims to optimize current supply policies to reduce transportation costs. The premise of this research is to optimize locations and supply policies to reduce transportation costs of various items found in the U.S. Navy inventory through an optimization tool (Burton, 2005, pp. 21–22). The model used is a mixed-integer optimization model written in the General Algebraic Modeling System. The model contains required delivery time parameter constraints.

Research by Burton (2005) relates to the work we present, in that both measure the impact of reducing transportation times of items ordered through a supply system (p. 11). Though Burton (2005) primarily focuses on minimizing transportation costs, implicitly the model formulation addresses the time it takes for supply deliveries by imposing a constraint on the Required Delivery Date (RDD) (pp. 25–26). The model also allows for variations in delivery times by assessing a penalty for items received outside the RDD, hence increasing costs (Burton, 2005, pp. 25–26). The underlying concept of delivery times affecting cost relates to the 1st MST R4 Process where wait time a home station unit experiences represents cost of a dollar value.

Another work is found in Santos (2003) on the U.S. Navy supply system. This work presents a model that looks at ways to improve the repair-turn-around-time of a subset of U.S. Navy supply inventory items. Santos identifies a flaw in the forecasting method used by the U.S. Navy in that it forecasts inventory levels for the next quarter based on the items repaired in the current quarter (2003, p. 15). This method of forecast neglects to account for the items still in the repair cycle, which does affect forecasting accuracy (Santos, 2003, p. 19).

Though the U.S. Navy no longer uses the supply system studied by Santos (2003), the techniques presented relate to our work. The times to process items by 1st MST only pertain to items that have completed processing. It does not adjust for items that are still in the processing pipeline. As we discuss in Chapter III, items still in the

processing pipeline do affect the time to process an item and should be considered. This is a straightforward example of censored data.

Another model related to our study is the model presented in Landry and Scott (2002). They build a simulation model of the Marine Corps Ground Equipment process and conduct sensitivity analysis to answer if a consolidation of maintenance facilities will reduce repair cycle time by certain percentages. Their work utilizes the queueing relationship known as Little's Law to determine the average number in queue by using the relationship that "inventory reduction is directly proportional to a reduction in repair cycle time" (Landry and Scott, 2002, p. 5). The term repair cycle time is referred in queueing literature as the average time in the system and the inventory represents the average number in queue. We use similar queueing theory principles in our thesis to assist us in modeling the 1st MST R4 Process. The work presented by Landry and Scott (2002) is similar to the method we pursue in modeling the 1st MST R4 Process in that a simulation output result is used to calibrate a queueing formula/model.

Hartmann (2001) presents an analysis of determining appropriate distributions. Hartmann examines whether it is appropriate to use repair time data for the German armored wheeled vehicle known as "Luchs" for prediction purposes within a simulation model. Hartmann concludes that the data is appropriate for prediction purposes and justifies this finding with effective parametric techniques (2001, p. 73). This work is similar to the work we present in our thesis,

in that it uses conclusions gained from exploratory data analysis to establish parameters for use in a simulation model. We also utilize similar parametric techniques to measure the appropriateness of using known distributions to model certain aspects of the maintenance process. We demonstrate a few of these techniques in Chapter III.

III. EXPLORATORY DATA ANALYSIS

This chapter addresses the available data related to the 1st MST R4 process. We perform exploratory data analysis to uncover pertinent relationships and information that assists in modeling the 1st MST R4 Process.

A. 1ST MST PROCESS

In Chapter I, we describe several actions taken by 1st MST in regard to OEF R4 that we can organize into phases. We identify a total of five phases to describe these actions as follows:

- Phase 1: the arrival of the equipment to 1st MST.
- Phase 2: basic processing, inspection, and repairs.
- Phase 3: procurement of all auxiliary SL-3 items.
- Phase 4: distribution instructions specifying which unit will receive the equipment.
- Phase 5: item is issued to a unit and the unit takes control of the equipment.

Figure 2 illustrates these five Phases. In this thesis, we intend to model the five phases, determine which are the key bottlenecks and explore what opportunities exist to reduce the time spent at any of the identified bottlenecks.

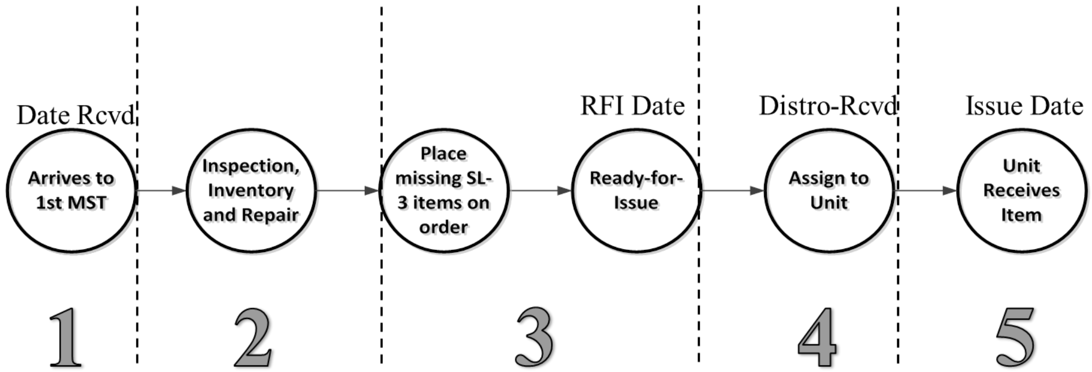

Figure 2. 1st MST R4 Process as identified by appropriate phases. Dotted lines separate the phases.

B. DATA

In January of 2013, we visited 1st MST and were able to learn their process and receive data. 1st MST provided us with data that allows us to calculate the time spent in some of the phases shown in Figure 2. The data consists of a file with 5,638 rows and 12 columns. The rows represent items received by 1st MST from November 17, 2011 through April 03, 2013. The columns represent information related to the equipment items that have arrived. It is important to note that not all 5638 items have made it through all 5 phases presented in Figure 2 by April 03, 2013.

Table 1 summarizes the seven factors regarding equipment items we examine in our analysis. TAMCN is "a grouping or range of items containing similar characteristics, have similar applications, and are susceptible to similar logistics management methods" in the USMC (USMC, 1994, p. 1-7). The first character of the TAMCN identifies the commodity area by a letter. We explain each commodity area in more detail in Appendix A.

Table 1. Key variables from 1st MST's data.

Columns of 1st MST Data Used in Thesis	
Title	**Explanation**
TAMCN	Used to identify the commodity area of the equipment item received (Appendix A).
Unit Name	Used to identify what unit received the reset equipment item after fully processed.
Date Received Reset	Arrival Day of the equipment item.
RFI Date	Day the equipment was ready-for-issue (RFI)
Distro Rcvd	Day the distribution instructions were received identifying which unit the item will belong to.
Issued Date	Day the gaining unit received the item, marks the end of 1st MST actions.

Each piece of equipment has four dates associated with it that drive most of our analysis:

- Date Received Reset: the equipment delivery arrival date.
- RFI Date: the day an item has been reset, SL-3 complete, and all repairs performed.
- Distribution Instructions Received Date: date the item is issued distribution instructions.
- Issue Date: the date item is issued to a unit.

We use these four dates to compute the time spent at each phase. The item spends zero time in Phase 1; immediately upon arrival it enters Phase 2. We can calculate how long each piece of equipment spends in Phase 4 and Phase 5, however we can only calculate the total amount of time spent in both Phases 2 and 3 together. We cannot separate the times in Phases 2 and 3 based on the data alone. We present estimations for the time spent in Phases 2 and 3 separately in Chapter IV.

Figure 3 breaks down the equipment received by 1st MST by TAMCN. TAMCN items of commodity area "A" make up close to 70 percent of the items received by 1st MST. These items are communication assets consisting primarily of radios. For most of our analysis we do not distinguish between different TAMCN categories; we treat all pieces of equipment as the same type. This is a shortcoming of the model and further research could extend this work to differentiate equipment by TAMCN. However, the same methodology we present in Chapters III and IV of this thesis would be applied to this extended model.

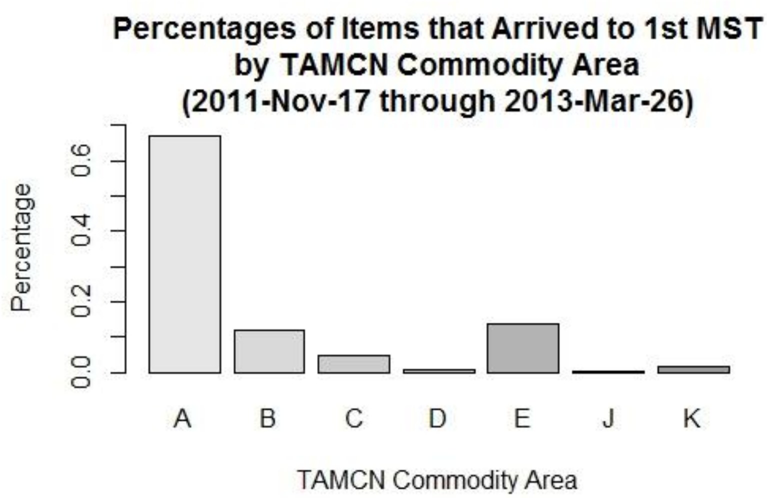

Figure 3. Amount of Items by TAMCN commodity area that arrived to 1st MST. Appendix A explains what each commodity area comprises of.

C. DATA ANALYSIS

In this section, we analyze the 1st MST R4 Process phases as described in Section A. We use parametric and non-parametric methods to gain insight into 1st MST operations to inform our model development in Chapter IV.

1. 1st MST Arrival Data

We first examine Phase 1 of the 1st MST R4 process: the arrival of equipment to 1st MST. We use 5633 out of 5638 equipment entries from the 1st MST Data. We removed five entries because they did not have an arrival date.

Figure 4 displays the number of pieces of equipment to arrive each day. 1st MST receives deliveries on 112 days out of a possible 496. On several days over 200 items arrive on the same day, which is not particularly surprising because equipment frequently arrives in large containers or pallets. Figure 4 shows a 56-day gap between the first and second delivery day. This is over three times larger than the next largest delivery gap (17 days). Figure 4 does not show any noticeable trend in how the arrival process changes over time.

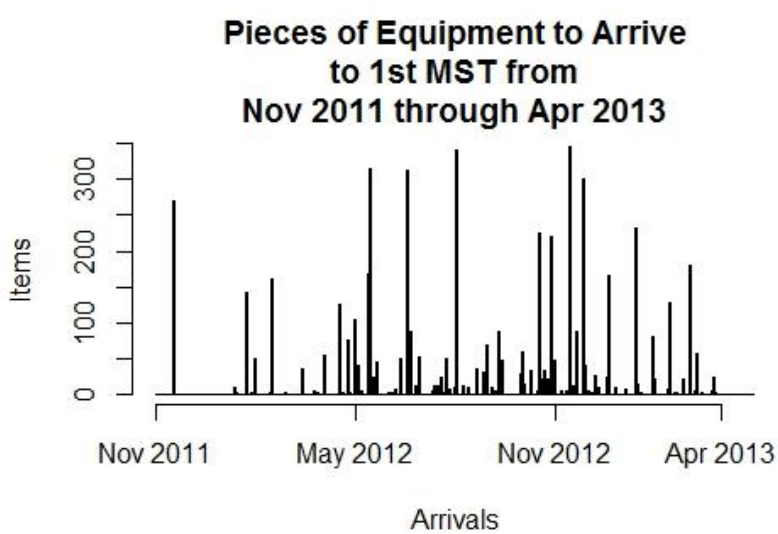

Figure 4. Histogram of pieces of equipment to arrive to 1st MST from November 2011 through April 2013.

To further investigate any trends in the pieces of equipment that arrive we look at a histogram with 30-day bins (Figure 5). No obvious arrival trend exists in Figure 5.

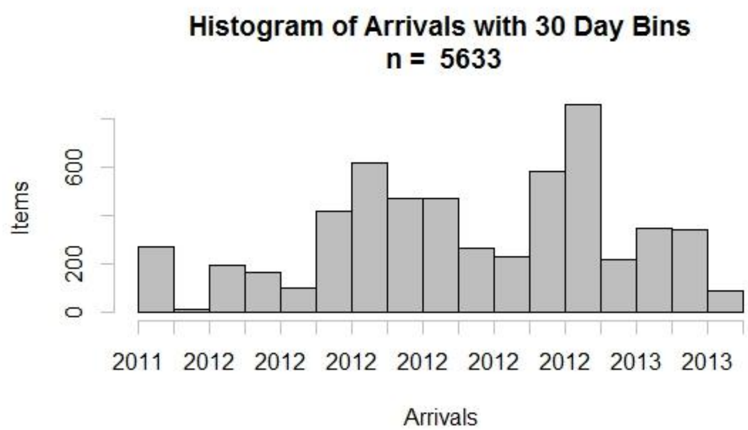

Figure 5. Histogram of equipment deliveries with 30-day bins. No obvious trend can be observed.

We next examine the inter-arrival times between delivery days after removing the first item delivery day, as this is clearly an outlier in the data set. The inter-arrival time is the time in between equipment item delivery days to 1st MST. We show the summary statistics as well as a histogram for this metric in Table 2 and Figure 6, respectively. The mean inter-arrival times of deliveries is 4 days with a standard deviation of 3.7 days.

Table 2. Summary Statistics for Inter-arrival times.

Inter-arrival Times Summary For Items Received by 1st MST	
Max Time between Deliveries	17.0 days
Median Time between Deliveries	3.0 days
Mean Time between Deliveries	4.0 days
Standard Deviation	3.7 days
Total Deliveries	111

Figure 6 shows a histogram of the inter-arrival times. The empirical standard deviation (3.7) is close to the empirical mean (4.0). This and the shape of the histogram in Figure 6 suggest the exponential distribution may be a reasonable representation of the inter-arrival times for deliveries.

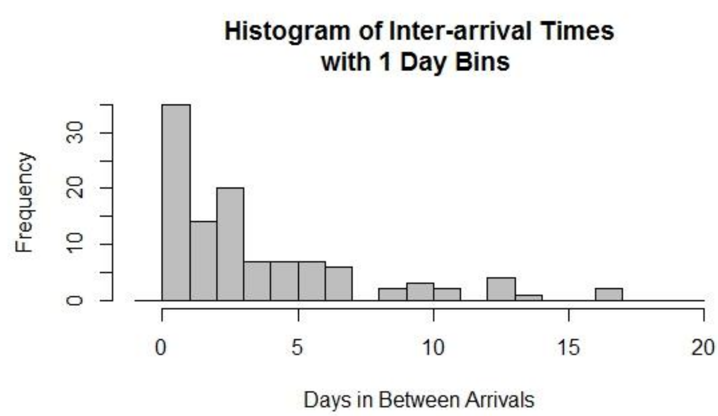

Figure 6. Histogram of inter-arrival times.

The exponential distribution has one parameter, λ, often called its rate and specified as:

$$\lambda = \frac{1}{E(\text{inter-arrival times})}.$$

Figure 7 presents the empirical probability mass function against the exponential probability density function with Maximum Likelihood Estimate (MLE):

$$\hat{\lambda} = \frac{1}{\text{mean inter-arrival time}} = .25$$

Figure 7 also displays a Quantile-Quantile (QQ) plot of exponential quantiles. In the QQ plot the solid line represents an exponential distribution with rate= .25 and the dots represent the empirical inter-arrival time distribution. Figure 7 suggests the exponential is a reasonable approximation.

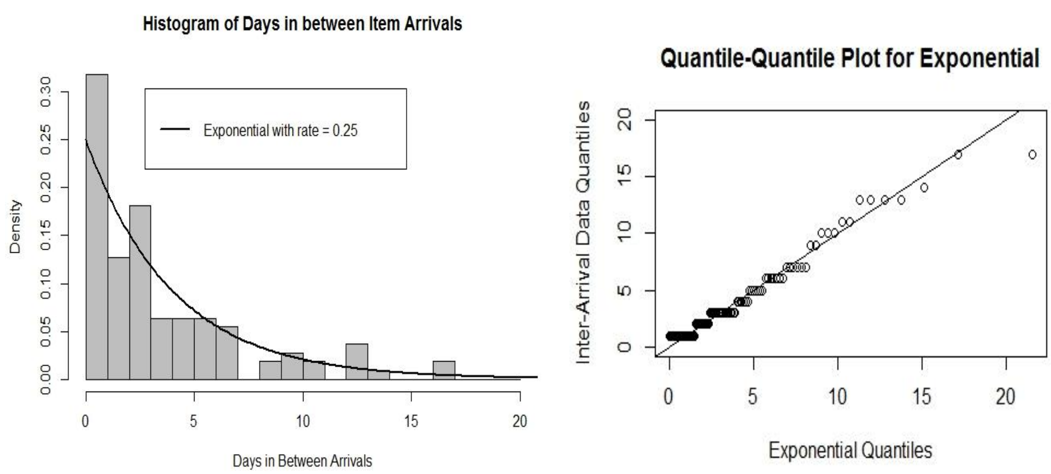

Figure 7. Histogram and QQ plot of inter-arrival times with an exponential fit.

While Figure 7 gives reasonable evidence that the exponential is a reasonable fit, we next perform a more rigorous goodness of fit test with the Pearson Chi-Squared (χ^2) test. The Pearson χ^2 test is used to test the following hypothesis:

$$H_0 = \quad \text{Sample comes from the theoretical distribution}$$
$$H_1 = \quad \text{The sample differs from the theoretical distribution} \;.$$

In essence, we discretize a continuous exponential distribution to compare it to our discrete data. We place each inter-arrival time into one of 6 equally sized bins between zero and 18 days, which provides a good spread of the inter-arrival data. This binned inter-arrival data is then compared to the expected number of the 111 data points that would fall in each bin if the data came from an exponential distribution with rate equal to 0.25. After performing the Pearson's χ^2 test, we generate a p-value of .1964. Since there is no evidence that the exponential is a poor fit, we assume that the inter-arrival time of deliveries to 1st MST follows an exponential distribution with rate = 0.25.

As shown in Figure 4 the number of items arriving per delivery exhibits no noticeable trend. We present a histogram in Figure 8 for the number of items that arrive in each delivery to 1st MST, using bins of size 20. Table 3 lists summary statistics for the amount of equipment delivered. There are a handful of very large deliveries consisting of several hundred items each. However, most deliveries are less than 20 items. The mean and standard deviation are 48 and 78.9, respectively. There is large variability in the number of equipment items in a delivery.

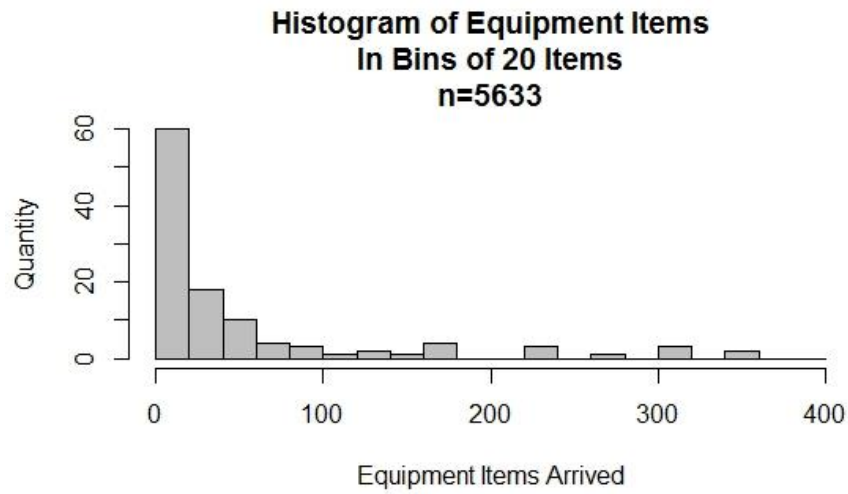

Figure 8. Histogram of number of equipment per delivery binned by 20 item bins.

Table 3. Summary statistics for equipment items per delivery.

Summary of Amount of Items per Delivery Received by 1st MST	
Max	346.0 items
Min	1.0 items
Median	13.0 items
Mean	48.0 items
Standard Deviation	78.9 items
n	111

2. Time to RFI

Phases 2 and 3 of the 1st MST R4 Process consist of equipment being inventoried and inspected (Phase 2), and obtaining SL-3 items to make the equipment SL-3 complete and RFI (Phase 3). An unfortunate aspect of the 1st MST data is that we cannot distinguish between the times of

these two phases. We define the time to RFI as the time between the arrival of the item to 1st MST and when the item has been properly reset by undergoing inspection, maintenance, and aggregation of its auxiliary SL-3 parts (Phases 2 and 3). We have a total of 3746 items in the data set that have been RFI.

Since the primary objective of 1st MST is to get an item into RFI condition, we compare the cumulative inflow of items to 1st MST and the cumulative flow of items to RFI status to examine if 1st MST is keeping up with the inflow of equipment items (Figure 9). Initially the equipment arrival rate outpaces the RFI rate, but then stabilizes around the 2000 item mark in late 2012 (Figure 9). The left hand side of Figure 9 shows the initial widening gap between the number of arrivals and the number of RFIs. The plot on the right presents the difference of the cumulative inflow and cumulative flow of equipment RFI.

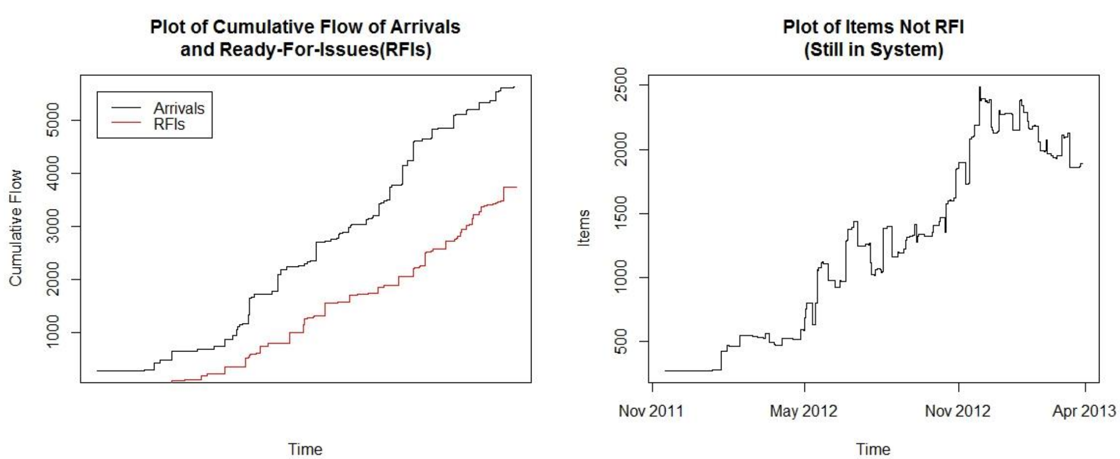

Figure 9. Left: Cumulative flow plot of item arrivals and ready-for-issues over time; suggests arrivals are initially outpacing the RFI rate. Right: plot of items in system that are not yet RFI; suggests the system is stabilizing with around 2000 items still

in the 1st MST R4 Process.

Figure 10 displays the histogram for the time to RFI in 50-day bins. The summary statistics appear in Table 4. The average time to RFI is 91 days, meaning approximately 3 months elapse from the time a piece of equipment arrives until all the processing and SL-3 completion occurs.

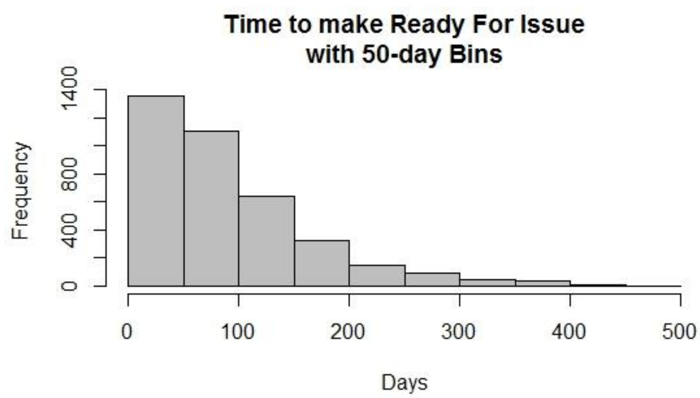

Figure 10. Histogram for RFI Time.

Table 4. Summary statistics for RFI Time.

Time Until Ready For Issue Summary For Items Received by 1st MST	
Max	428.0 days
Min	1.0 day*
Median	77.0 days
Mean	91.0 days
Standard Deviation	75.5 days
n	3746
*Four entries have zero day in data but 1 day imputed for time to Ready For Issue. This is because Ready For Issue occurred on same day item was received by 1st MST.	

While we do not have enough information to separate Phase 2 and Phase 3 from the MST data, we do have additional data on the amount of time it takes to receive ordered SL-3 parts. As explained in Chapter I, 1st MST can obtain SL-3 items from four different sources, with the longest wait coming from DLA and GSA. We have data for equipment obtained from DLA or GSA consisting of 2058 total items ordered by 1st MST over the time period of interest. This data also contains the number of days required to fill the order and arrive to 1st MST. MCLC provided the data, which is derived from information within the Maintenance Data System that contains records for all parts ordered by a repair facility in support of Marine Corps units. The summary statistics for this data appear in Table 5 after combining DLA and GSA, henceforth annotated as DLA/GSA.

The mean time to receive an SL-3 item from DLA/GSA is 39 days with a standard deviation of 53 days. The maximum time is nearly 400 days. A histogram of this data suggests a lognormal distribution may be an appropriate fit to the data (Figure 11). In Figure 11 we show the Empirical Cumulative Distribution Function (ECDF) of the time to fill an order from DLA/GSA and also a plot of a lognormal with MLE parameters of (3.59, 0.877). We will use this lognormal distribution to represent the time to fill an order from DLA/GSA in Chapter IV. We now proceed with discussing a biasing effect we uncovered during our analysis.

Table 5. Summary Statistics for elapsed time for items filled by DLA/GSA.

Summary Statistics for Elapsed Time of items filled by DLA/GSA	
Max Elapsed Time	394.0 days
Min Elapsed Time	7.0 days
Median Elapsed Time	19.0 days
Mean of Elapsed Time	38.7 days
Standard Deviation of Elapsed Time	52.6 days
n	2058

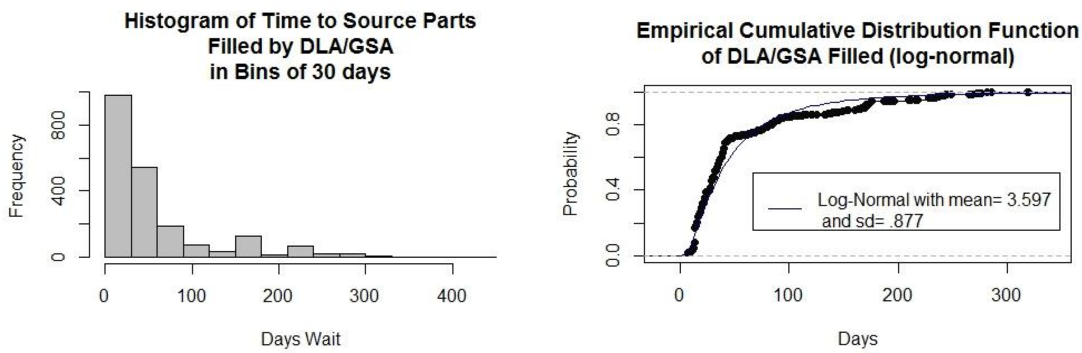

Figure 11. Left: Histogram of time to source parts filled by DLA/GSA. Right: ECDF of elapsed time to receive items filled by DLA/GSA compared to a lognormal Cumulative Distribution Function.

As a consequence of using only items that 1st MST has RFI’d, a biasing effect exists in the analysis of this data. That is the numbers in Table 4 do not account for the items still in the 1st MST system. This will lead to an underestimate of the time it takes MST to fully process and issue the equipment. These numbers are used for planning and forecasts purposes. Technically we have right-censored data and handle this by using a non-parametric approach: the Kaplan-Meier survival curve (Crawley, 2013, p. 869).

The Kaplan-Meier survival analysis is a common technique used in situations where the data is truncated and not all observations have completed the process under consideration (Sprent & Smeeton, 2007, p. 267). In the traditional nomenclature, an observation is either classified as a "death" or "at-risk." A death signifies that an observation departs the system and those at-risk are observations that are still in the system. In our case a death signifies when an item becomes RFI. Those considered at risk are the equipment items still awaiting processing and SL-3 completion (Phase 2 or 3) as of April 03, 2013.

Survival analysis estimates the Kaplan-Meier survivor function $\hat{S}_{KM}$, used to generate the survivorship:

$$\hat{S}_{KM}(t) = \prod_{t_i < t} \frac{r(t_i) - d(t_i)}{r(t_i)},$$

where $r(t_i)$ are the number still in the system at time t_i and $d(t_i)$ are the number of observations that have reached an RFI status by time t_i (Crawley, 2013, p. 876). $\hat{S}_{KM}$ is an estimate of the complementary Cumulative Distribution Function (CDF) of the time to become RFI

$$\hat{S}_{KM}(t) = 1 - F(t).$$

We use the R statistical package *Survival* to generate the Kaplan-Meier curve. Once we have this curve we can estimate the mean time to RFI from the uncensored distribution. We do this by calculating the area under the Kaplan-Meier curve. This follows because the mean of a positive random variable can be calculated by integrating

its complementary CDF (Ross, 2010, p. 91). The plot of the survivor function $\hat{S}_{KM}$ after using the Kaplan-Meier method, referred to as uncensored data, appears in Figure 12. We also show a plot of the survivor function calculated from only the 3746 RFI observations in Figure 12. We refer to this as the censored data. There clearly is a significant difference between these curves, which suggests the censoring is not trivial.

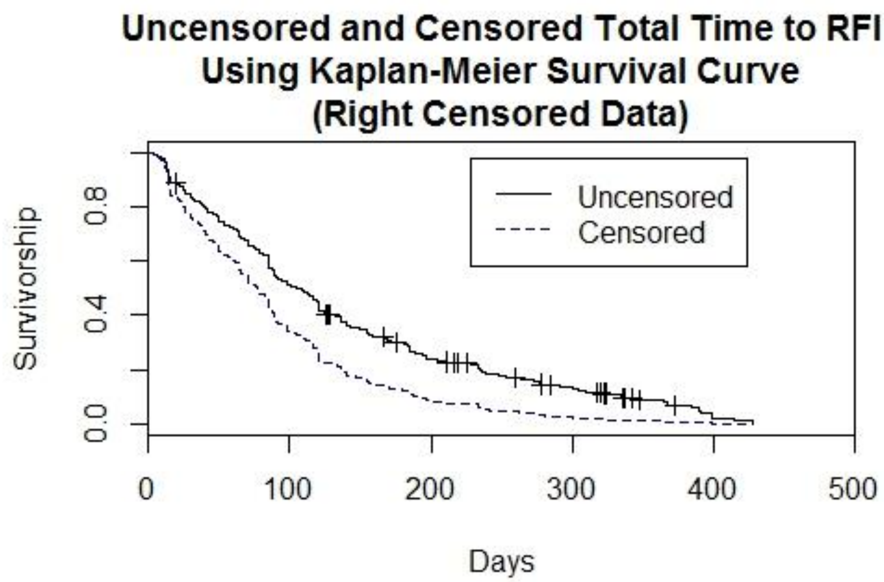

Figure 12. Plot of Kaplan-Meier survivorship curve for both uncensored and censored time to RFI. The uncensored curve adjusts for censored entries. The tic marks on the uncensored curve are occasions when censored entries are encountered.

The estimated mean for the uncensored time to RFI generated from the Kaplan-Meier estimate is 140 days with a standard error of 1.8. This mean is over 50 percent greater than the censored estimate of 91 days. This suggests that

the actual average time to RFI is much greater than currently estimated.

This can have significant consequences for planning and forecasting purposes. For instance, a great portion of 1st MST operations requires the use of civilian/government contractors. If contract scheduling relied on this metric, an underestimate in manpower requirement by almost two months could be the result. Also as OEF R4 draws down the average RFI time could increase not because of inefficiencies in the 1st MST R4 Process but because of the impact from this censoring of equipment items. The importance of this finding cannot be overstated for our analysis.

The median of the uncensored time to RFI is listed as 105 days (median of censored time to RFI is 77 days), so the distribution is substantially right-skewed. This suggests there are a small fraction of items that take a long time to process and they are not adequately represented by the RFI data. We show the summary statistics of the uncensored time to RFI in Table 6. We now discuss the next Phase of the 1st MST R4 Process.

Table 6. Summary statistics of uncensored time to RFI

Summary of Uncensored Time to RFI	
Mean*	140 days
Standard Error of Mean*	1.84 days
Median	105 days
n	5513 items
*Mean is identified as the relative mean in survfit, the function used from the R statistical package to populate the mean when accounting for censored data.	

3. Time to Receive Distribution Instructions

After 1st MST RFIs an item, I MEF G-4 must specify the distribution instructions to designate which unit the equipment will go to. This is Phase 4 in the MST process. The time to complete Phase 4 involves administrative tasks, examining items possessed within subordinate unit supply accounts, and discussions with particular units about their equipment needs. We refer to this as the time to receive distribution instructions. We use 3736 total equipment item observations for this portion of the analysis, excluding items that have not yet received distribution instructions.

Figure 13 shows the histogram of the time to receive distribution instructions and Table 7 presents the summary statistics. Figure 13 depicts a large number of zero days, signifying Phase 4 was completed in less than 24 hours. The mean of this data is 7.3 days with a median value of 9 days as shown in Table 7.

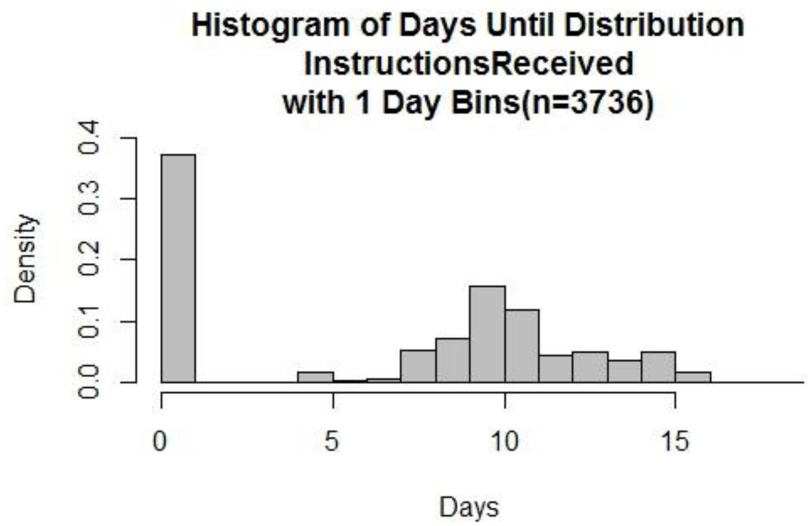

Figure 13. Histogram of days until distribution instructions received with 1-day bins.

Table 7. Summary statistics for time to receive distribution instructions.

Summary of Time to Receive Distributions Instructions for Items Received by 1st MST	
Max Time	94 days
Min Time	0 days
Median Time	9 days
Mean Time	7.3 days
Standard Deviation	7.3 days
n	3736

4. Time to Issue to Unit

After I MEF G-4 assigns an item to a unit, the unit is then responsible for retrieving the item from 1st MST. This is Phase 5 of the 1st MST R4 Process. In general, 1st MST wants the unit to pick up the equipment item within a week. We have a total of 3631 items that we use during this portion of the analysis, excluding items with errant records or if they have not yet been issued. The histogram for the time to issue appears in Figure 14.

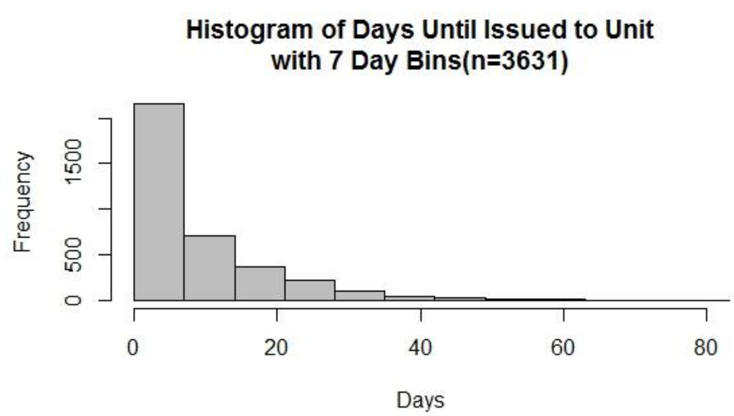

Figure 14. Histogram of time to issue shown with 7-day bins.

Table 8 contains the summary statistics for time to issue. The mean time of approximately 9 days is a little higher than desired but does include weekends.

Table 8. Summary of time to issue to a unit.

Summary of Time to Issue to Unit for Items Received by 1st MST	
Max Time	127 days
Min Time	0 days
Median Time	6 days
Mean Time	8.9 days
Standard Deviation	10.9 days
n	3631

D. TOTAL TIME TO PROCESS AN ITEM

The analysis in this chapter indicates the RFI time is the key factor of the 1st MST R4 Process. If the time it takes equipment to reach the I MEF home station unit is to be reduced, Phases 2 and 3 of the 1st MST R4 Process need to decrease. The analysis shows that the uncensored time to RFI median is slightly over 3 months with a mean of almost 5 months. Also shown in the analysis is that the mean time to receive distribution instructions and to issue an item combined are approximately 10 to 20 days. This is an order of magnitude less than the time to RFI. This leads us to focus on Phases 2 and 3 in our modeling in Chapter 4 because changes to Phases 4 and 5 will have limited impact on the total time to process an item.

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IV. MODEL

This chapter utilizes the insights gained from our visit with the 1st MST team and the analysis in Chapter III to formulate a mathematical model of the 1st MST R4 process. After formulating the model we identify the key factors that determine the total time in the MST system. We perform sensitivity analysis to pinpoint how this time can be effectively reduced.

A. 1ST MST R4 PROCESS MODEL

Figure 15 summarizes the average time spent in each Phase of the process identified in Chapter III after accounting for censored data. The largest time, 140 days is spent waiting to RFI an item (Phases 2 and 3). We focus the majority of our modeling on Phases 2 and 3 and aim to analyze the driving factors of these Phases by modeling the two phases separately. Phase 2 and 3 will consist of two separate modeling components, one utilizing queueing principles (Phase 2) and the other utilizing Extreme Value Theory (EVT) (Phase 3). The subsequent phases, the distribution instructions and issue to unit can be treated as constants and are not modeled (Phases 4 and 5).

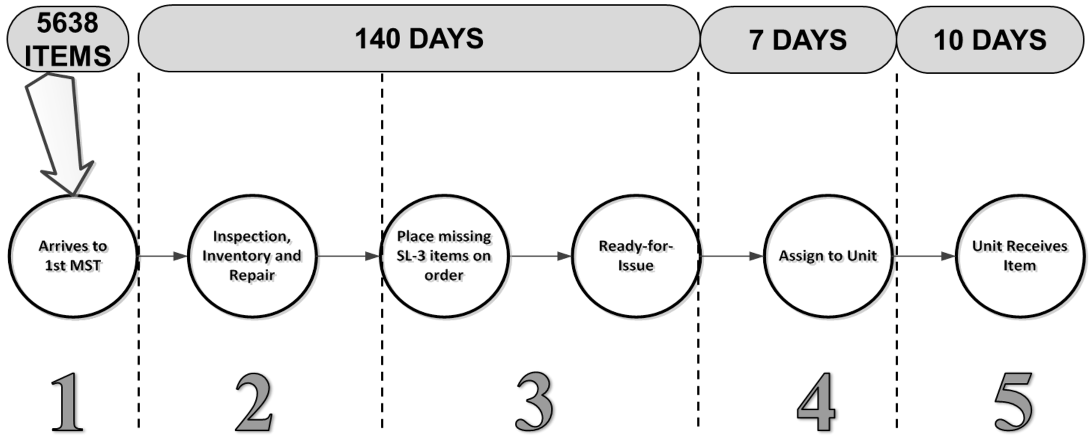

Figure 15. Summary of 1st MST R4 Process with uncensored time found by using the Kaplan-Meier relative mean estimate. The Phases 1 through 5 are also listed. Dotted lines separate the phases.

B. ESTIMATING THE EXPECTED SERVICE TIME

As discussed in Chapter III, many items can be delivered in the same day. In reality these items arrive in pallets or containers, are unloaded, inventoried and eventually go through inspection and repair. We assume for simplicity that one team does the processing and handling of the items in a first-in first-out manner, and hence we formulate a queueing model for this phase.

Items arrive to 1st MST in bulk deliveries as shown in Table 3. Furthermore inter-arrival times are reasonably represented by an exponential (Figure 4, Figure 7), so we can assume deliveries occur according to a Poisson Process. We have no specific knowledge of the service time distribution, thus we use an M/G/1 queueing model with random-sized batch arrivals to model Phase 2 of the 1st MST R4 Process. The summary statistics found in Table 3 are used to assist us in modeling the batch arrival portion of

the model. We now present the M/G/1 batch model we use as contained in Ross (2010, pp. 538–543).

The M/G/1 with random-sized batch arrivals assumes arrivals occur as a Poisson Process having an arrival rate of λ, a general service distribution, and a single server. However, an arrival does not consist of one customer, but a random number of customers. We discuss the specific service distribution in greater detail later in this chapter.

Concerning the single-server assumption, from what we observe it is truly more of a team effort, rather than independent parallel server stations throughout the reset process. This may be an oversimplification, however we feel to further refine the maintenance process to several servers would make the modeling process much more complex without generating additional insight. Future work could develop a simulation model to account for multiple servers. We now discuss several performance measures related to the random-sized batch arrival M/G/1.

The model presented in Ross (2010, p. 543) begins with calculations for the total time a customer takes to move through the system which we denote as T_Q:

$$T_Q = \frac{E[S](E[N^2] - E[N]/2E[N] + \lambda E[N]E[S^2]/2}{1 - \lambda E[N]E[S]} + E[S]. \tag{1}$$

In Equation (1) N is a random variable identifying the size of a batch, S is the service time, and λ is equal to the arrival rate (Ross, 2010 p. 543).

We use the M/G/1 random-sized batch arrival model to calculate T_Q, by using the parameter information we already

estimated in Chapter III: $\hat{\lambda}$, $E[N]$, and $E[N^2]$. $E[N^2]$ is the second moment defined as $Var(N)+(E[N])^2$. However, we have no data or knowledge about the service time distribution S, and hence cannot calculate expected service time $E[S]$ and the second moment calculation of $E[S^2]$. We will attempt to estimate $E[S]$ and $E[S^2]$ by first estimating T_Q, from Equation (1).

To estimate T_Q we first define T_{RFI}, time to RFI an item as:

$$T_{RFI} = T_Q + T_{SL-3},$$

where T_{SL-3} is the time to receive missing SL-3 items. We only have data for T_{RFI}, an aggregate including T_{SL-3} and T_Q adding to the difficulty in calculating $E[S]$. We estimated T_{RFI} in chapter III (Table 6) and present an estimate of T_{SL-3} in the next section, thus

$$T_Q = T_{RFI} - T_{SL-3}.$$

Once we have T_Q we can then back out $E[S]$ from Equation (1).

Unfortunately Equation (1) also requires knowledge of $E[S^2]$, which we do not have. We choose to redefine equation (1) in terms of the coefficient of variation of S rather than $E[S^2]$. The coefficient of variation represented by the variable cv is defined as follows:

$$cv = \frac{\text{standard deviation}(S)}{E[S]}.$$

We can now express Equation (1) in terms of cv and solve for $E[S]$. This derivation results in a quadratic equation for $E[S]$,

$$\lambda E[N](1-\frac{(cv^2+1)}{2})E[S]^2-(T_Q\lambda E[N]+1+\frac{E[N^2]-E[N]}{2E[N]})E[S]+T_Q=0 . \qquad (2)$$

Through the use of the quadratic formula, a value can be generated for any value of cv, providing a general understanding of $E[S]$. See Appendix B, for more details on the solution to Equation (2). We set $cv=1$ as our base case. The exponential has a coefficient of variation of 1. As can be seen, besides inputting a cv value into Equation (2) we must also input T_Q. We set T_Q to the total time in system up to when an item reaches RFI status (Phases 1 through 3) after subtracting any T_{SL-3}, therefore setting $T_Q = 140 \text{ days} - T_{SL-3}$. So if we can solve for T_{SL-3}, then we can identify T_Q. We now discuss this process.

C. MODELING TIME AWAITING SL-3

Based on our visit and conversations with 1st MST personnel, T_{SL-3} takes significantly more time than processing/repairing an equipment item. This appears to be a major concern for the 1st MST leadership and a large component of overall total time in system. Unfortunately, the MST data does not explicitly capture the time required to obtain all the SL-3 items. In this section we estimate the average time to make an item SL-3 complete using the limited information we have.

As previously mentioned, missing SL-3 item requisitions are filled by several sources of supply: 1st

MST's PEB, SMU, MCLC, and DLA/GSA. For simplicity we consolidate DLA/GSA so that there are four main sources of supply for consideration. Concerning the SL-3 amount, from the information we gather, the expected number of SL-3 items associated with an item is approximately 50 items and ranges from approximately 10 to 100 items. We choose to represent this number with a triangular distribution with a low value of 10, high value of 100 and mode of 50. We estimate that approximately 80 percent of the required SL-3 items are missing per item. The missing SL-3 items are ordered from one of the four main sources of supply.

Based on observations and conversations with 1st MST personnel, we estimate that each source of supply is utilized in the following percentages: 10, 75, 5, and 10 signifying that approximately 10 percent of missing items are obtained from the PEB, 75 percent from the SMU, five percent from MCLC and 10 percent from DLA/GSA. We also observe that 1st MST receives an item immediately from 1st MST PEB, in 1 to 2 days from the I MEF SMU, in 7–10 days if filled from MCLC, and often over 30 days if filled from DLA/GSA. As shown in Section C of Chapter III, we use the lognormal distribution as an approximation for DLA/GSA. A summary of the four sources of supply and the appropriate random distributions we use appear in Table 9.

Table 9. Summary of information regarding four sources of supply used in estimating T_{SL-3}.

Summary of Four Sources Of Supply (BASE CASE)			
Source	**Percentage Used**	**Time Required (days)**	**Random Distribution Used**
1st MST PEB	10	Less than 1	Uniform
I MEF SMU	75	1 to 2	Uniform
MCLC	5	7 to 10	Uniform
DLA/GSA*	10	7 to more than 30	Log-Normal (meanlog=3.59, sdlog=.877)
*DLA and GSA orders are combined as one source of supply			

As previously stated, 1st MST cannot RFI an item until it is SL-3 complete. Thus if we associate with each SL-3 item a wait time to receive the item, then T_{SL-3} will be the maximum of those wait times. This suggests utilizing EVT. Results from EVT state that the CDF of the maximum of a deterministic number of Independent and Identically Distributed (IID) random variables can be found by raising the CDF of one of the random variables to an appropriate power (Haan & Ferreira, 2006, pp. 3–4). We derive this result below:

$$\begin{aligned}
&\text{Let } Y_{\max} = \max\{Y_1,...,Y\} && \text{maximum of a sequence of IID random variables} \\
&F_{Y_{\max}}(y) = P(Y_{\max} \le y) && \\
&\qquad = P(Y_1 \le y, Y_2 \le y, ..., Y_n \le y) && \quad (3) \\
&\qquad = P(Y_1 \le y)P(Y_2 \le y,)...P(Y_n \le y) && \text{by independence} \\
&\qquad = F_Y(y)^n && \text{because IID.}
\end{aligned}$$

The above can be generalized if the random variables are all independent, but they consist of several distinct distributions. For example if there were two categories of random variables, the CDF of the maximum would take the

form of $F_y(y)^n F_x(x)^m$. This multiple category situation would be appropriate for the MST scenario where there are four sources of SL-3 items.

The 1st MST problem is more complex than the standard extreme value result in Equation (3) because the number of SL-3 parts is not deterministic. The result can be further generalized by using the law of total expectation (Ross, 2010, p.107) and conditioning on the number of SL-3 items received. In theory we could write down an expression for the CDF of the SL-3 completion time and then numerically integrate it to compute T_{SL-3}. However, that would be fairly tedious and instead we use simulation to estimate this parameter. The T_{SL-3} estimate we generate from this procedure is approximately 105 days.

D. MODEL BASE CASE

We now focus on the key factors driving T_{RFI} and describe a base case for our model. From what has been discussed to this point we are able to estimate: the arrival rate $\hat{\lambda}$, uncensored time to RFI an item T_{RFI}, T_Q, T_{SL-3} and the expected service time $E[\hat{S}]$ through use of a coefficient of variation cv.

By using cv equal to one, which can be considered a service time from the exponential distribution, and substituting all known estimates into Equation (2) we generate an $E[\hat{S}] = .0658$ days per item. This equates to an expected service time of approximately two hours per item. Adjusting the cv from zero to twenty has a minor effect on

$E[\hat{S}]$ (Figure 16). As a result of such a small effect, we use a cv equal to one throughout this section.

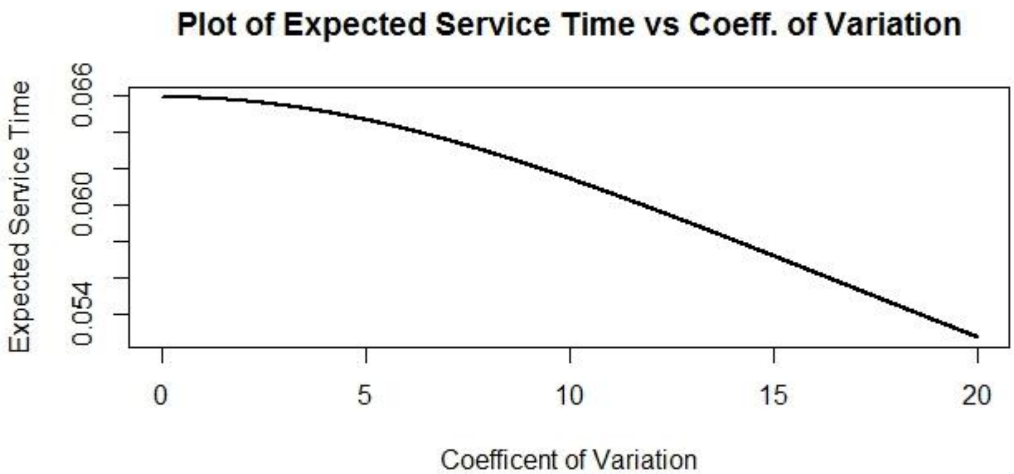

Figure 16. Plot of expected service time versus coefficient of variation. Coefficient of variation is varied from zero to 20.

We present our base case findings in Table 10. We think the values found in Table 10 seem reasonable from what we ascertain from the 1st MST data. Unfortunately, we are not able to perform a rigorous validation because Phase 2 and Phase 3 cannot be separated.

Table 10. Summary of base case parameters and initial estimates.

Base Case Parameter Values	
T_{RFI}	140 days*
$\hat{\lambda}$	0.25
cv	1
T_{SL-3}	105 days**
$E[\hat{S}]$	0.0658 days
*Uncensored mean **10,000 simulated runs	

As shown in Table 10, T_{SL-3} is a significant component of the time to process an item and makes up approximately 75 percent of the T_{RFI} $(\frac{105}{140}=.75)$. This certainly warrants close study to determine what factors could most effectively reduce T_{SL-3}. We now perform sensitivity analysis on T_{SL-3} and present our findings in the next section.

E. SENSITIVITY ANALYSIS

We now perform sensitivity analysis focused on T_{SL-3}, the largest proportion of T_{RFI}. We observe that the driving factor causing a high T_{SL-3} is the wait time of the SL-3 parts filled by the DLA/GSA supply source (Table 9). In fact, if the three supply sources PEB, SMU, and MCLC became immediately sourced SL-3 items, the 105 day T_{SL-3} would still occur. This makes sense because as previously explained, an item will have to wait until the last ordered item arrives and items from the DLA/GSA supply source take significantly longer to fill. In the base case, DLA/GSA supplies 10

percent of the required missing SL-3. We look at the effect on T_{RFI} from shifting the percentage of items filled by DLA/GSA to the three other sources (Figure 17).

As we adjust the percentage of DLA/GSA filled items from zero percent to 20 percent it is immediately visible that any percentage decrease of DLA/GSA filled items decreases T_{RFI}. The percentage remaining after decreasing DLA/GSA filled items are allocated proportionally to the three other sources of supply. If 1st MST can reduce the percentage of items DLA/GSA fills from ten to five, the T_{RFI} is expected to be reduced by approximately 40 days. It is important to note that T_{RFI} will never decrease lower than $T_Q = 35 \text{ days}$. Even if all SL-3 items are obtained instantaneously the items must still go through the initial processing. What is also evident from Figure 17 is the steady increase in T_{RFI} for any increase greater than the base case percentage. We now look at the effect of changing the percentage of SL-3 items missing.

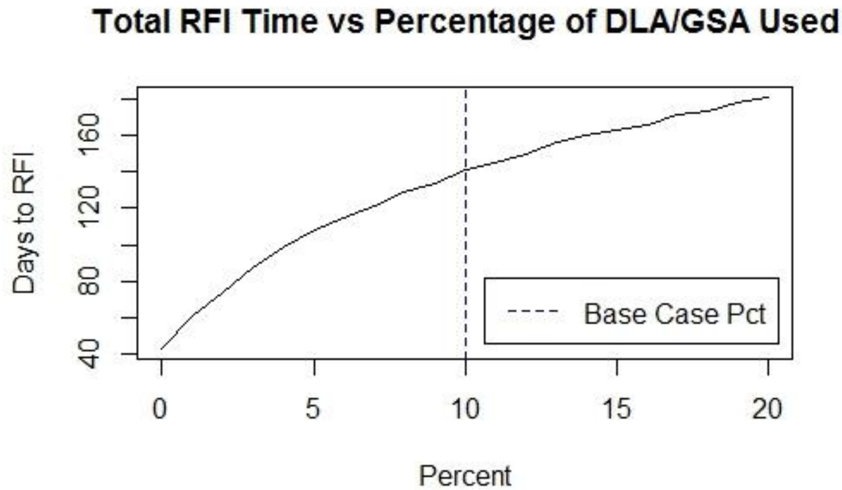

Figure 17. Plot of adjusting the percentage of items DLA/GSA is required to fill by shifting requirements to the three other sources of supply.

As previously expressed, it is estimated that each piece of equipment only has 20 percent of its associated SL-3 items upon arrival to 1st MST. We look at the effect of varying the percentage of SL-3 items arriving with an item being reset as shown in Figure 18. It is immediately evident that the fraction of missing SL-3 items does have a significant effect on T_{RFI}.

Figure 18 shows that if no SL-3 items are missing, hence the item is SL-3 complete, the T_{RFI} is 35 days which is our estimate of T_Q. We do not think this is a realistic and attainable value. What seems to be more attainable is if an item has 80 percent of its SL-3 components. This change in the percentage of SL-3 reduces the T_{RFI} by approximately two months.

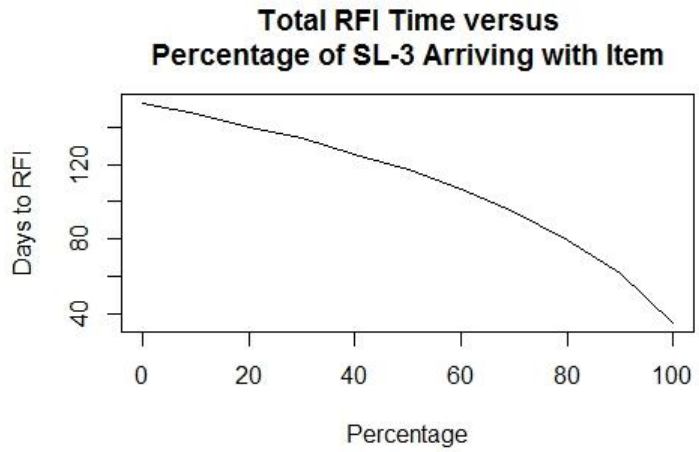

Figure 18. Plot of Total RFI time as the percentage of SL-3 items arriving with item when varied from zero to 100 percent.

Due to our assessment findings that DLA/GSA sourced items are the bottleneck of the 1st MST R4 process, we look at adjustments to the distribution we use to model the wait times filled by this source of supply. We adjust the mean for the lognormal distribution used to represent SL-3 wait times for DLA/GSA, thus changing the time it takes to receive an item from DLA/GSA. The mean for the lognormal is calculated as $e^{\mu+\frac{\sigma^2}{2}}$. We show how T_{RFI} varies with the mean of this lognormal random variable in Figure 19. The base case value of approximately 53 days is shown in Figure 19 as the dashed red vertical line. The graph reveals a fairly linear relationship between the mean and time to RFI. The Figure suggests that if the mean wait time could be reduced to 30 days, T_{RFI} could be reduced by approximately two months.

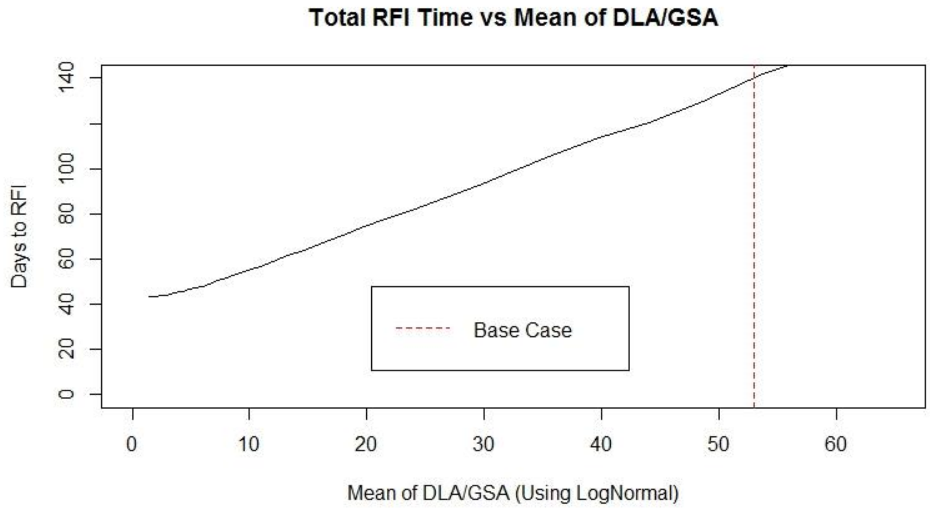

Figure 19. Plot of total time to RFI versus mean of lognormal distribution used to determine DLA/GSA wait times.

V. CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

As the drawdown of U.S. military presence in Afghanistan continues, attention to improving readiness via the R4 of ground equipment emerges as a top priority to ensure the USMC remains a "force in readiness" and postured for our Nation's next demands. It is clear that the USMC units in CONUS are in a degraded supply status, and that the USMC does not have the fiscal ability to purchase all new ground equipment to replenish its units. The R4 of ground equipment returning from Afghanistan then emerges as a primary means to improve USMC readiness. We model 1st MST's processing of R4 equipment in five phases and determine how long the equipment takes to reach the warfighter.

In the process of analyzing 1st MST we discover that naively using only items that have been RFI'd will produce a biased estimate of the average time to RFI an item due to censoring. We address this censoring via the Kaplan-Meier method and derive a T_{RFI} of 140 days. This component dominates the other phases of the 1st MST R4 Process. We show that the arrival rate of equipment to 1st MST can be represented with an exponential distribution of rate equal to 0.25. We also present methods involving queueing theory and model the 1st MST R4 Process with an M/G/1 random-sized batch arrival model. We estimate T_{SL-3} at 105 days after utilizing EVT aided by simulation, which is 75 percent of T_{RFI}. We conclude with the finding that T_{SL-3} is a very large

component of the overall mean time an item spends in the system and present what we perceive as the driving factors causing such a large time. We now present our recommendations based on the analysis findings.

B. RECOMMENDATIONS AND FURTHER STUDY

As we demonstrate in Chapter IV Section E, if the fraction of SL-3 items obtained from DLA/GSA decreases and 1st MST obtains proportionally more SL-3 items from the other three supply sources, there is a significant decrease in T_{RFI}. We recommend I MEF take actions to increase the number of SL-3 items available in 1st MST’s PEB or in the SMU. This may require further study of the stocking policies at these locations and the forecasting methods used to inform the stocking decisions. Improved forecasting and stocking decisions may provide improved support for missing SL-3 items and decrease overall T_{RFI}.

Another significant factor that affects T_{RFI}, is the number of missing SL-3 items per item that arrives to 1st MST. We recommend I MEF and MCLC take actions to reduce the number of SL-3 items missing per piece of equipment. This would have to be addressed in Afghanistan. If R4OG or MCLC FWD identifies equipment with missing SL-3 items during their inspections, those missing SL-3 items could be ordered ahead of time on behalf of the home station unit that the equipment will be assigned to. This could save the MST time during the R4 process. We also suggest performing trend analysis on items that arrive with missing SL-3 and map their itineraries from Afghanistan to identify any

units that return equipment in the OEF R4 process with far more missing SL-3 than the norm.

Our analysis has several shortcomings that could be addressed in future work. One shortcoming is how we handle the different TAMCN commodity areas. As described in Chapter III, we group all TAMCN commodity areas together during our analysis. A more precise method would look at each commodity area separately. Future work could also more carefully consider the number of service teams utilized at 1st MST. We assume one server is present in the 1st MST R4 Process. That seems like a reasonable first approximation, but additional research could study whether it would be more appropriate to consider a system with several servers in parallel.

We received valuable data regarding the 1st MST R4 Process. However, the data did not capture information about all components of our analysis. More definitive data regarding Phase 2 and 3, the fraction of each type of supply source used, and the length of time taken to receive items from the supply sources would assist in developing an improved and more accurate model and would improve validation efforts. We also focused on the mean time it takes an item to move through the 1st MST. Further research could examine other aspects of the distribution, such as the variance. One would need to examine any dependencies in the time an item spends in each phase of the process. For example perhaps items that spend a longer time in Phases 2 and 3, also spend a longer time in Phases 4 and 5. Finally, in computing the mean time in Phase 2 we used a standard result from queueing theory. However, that quantity is the

steady state average time in a queueing system. One could argue some of the data we have captures transient effects. Future work could attempt to disentangle transient and steady state aspects of the data.

APPENDIX A. COMMODITY AREAS

Commodity Area. Refers to a grouping or range of items containing similar characteristics, utilized in similar applications, and managed by similar logistics methods. The Marine Corps uses the first position of the TAMCN to designate commodity areas as follows:
Communication and Electronics (C&E): A, H, and T.
Engineer (Eng): B, J, and U.
General Supply (GS): C, K, and V.
Motor Transport (MT): D, M, and W.
Ordnance (Ord): E, N, and X.
Nuclear, Biological, Chemical (NBC): A, B, C, H, J, K,T, U, and V.
Garrison Mobile Equipment (GME): G.

(From USMC, 1994)

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APPENDIX B. SOLUTION OF EQUATION (2)

Beginning with Equation (1), and the M/G/1 random-sized batch arrival model presented in Ross (2010):

$$T_Q = \frac{E[S](E[N^2]-E[N]/2E[N]+\lambda E[N]E[S^2]/2}{1-\lambda E[N]E[S]} + E(S)$$

and cv the below follows:

$$cv = \frac{\text{standard deviation}(S)}{E[S]}$$

$$T_Q = \frac{\dfrac{E[S](E[N^2]-E[N])}{2E[N]} + \lambda\dfrac{(cv^2+1)E[N]E[S]^2}{2}}{1-\lambda E[N]E[S]} + E[S] \Rightarrow$$

$$T_Q - T_Q\lambda E[N]E[S] = \frac{E[S](E[N^2]-E[N])}{2E[N]} + \frac{\lambda(cv^2+1)E[N]E[S]^2}{2} + E[S] - \lambda E[N]E[S]^2 \Rightarrow$$

Combining Terms yields:

$$\lambda E[N](1-\frac{(cv^2+1)}{2})E[S]^2 - (W\lambda E[N]+1+\frac{E[N^2]-E[N]}{2E[N]})E(S) + T_Q = 0$$

If we let,

$$a = \lambda E[N](1-\frac{(cv^2+1)}{2})$$

$$b = -(T_Q\lambda E[N]+1+\frac{E[N^2]-E[N]}{2E[N]})$$

$$c = T_Q$$

use of the quadratic formula results in:

$$E[S] = \frac{-b \pm \sqrt{b^2-4ac}}{2a}.$$

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